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Towards the quantification of energy demand and consumption through the adaptive comfort approach in mixed mode office buildings considering climate change

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ABSTRACT

Heating, Ventilating and Air Conditioning (HVAC) systems represent one of the highest energy consumptions for office buildings. They are traditionally based on fixed setpoint temperatures during working hours and disregard outdoor conditions. The use of natural ventilation coupled with HVAC systems is frequently proposed when considering the global tendency towards reducing energy consumption in buildings. Buildings working under mixed mode instead of full air-conditioned mode, are a climate adaption development and usually lead to a decrease in energy consumption. However, there is no consensus on comfort thresholds and it is difficult to predict energy demand and consumption when considering global warming. This research focuses on quantifying the application of an adaptive comfort control mode in mixed mode office buildings. It consists of using daily setpoint temperatures based on the adaptive thermal comfort approach, in both present and future scenarios. The results show a 74.6% reduction in energy demand and a 59.7% drop in energy consumption when the adaptive comfort control implemented model (ACCIM) is applied in the current scenario. Results also establish that the ACCIM is more resilient to climate change, despite the fact that an increase in energy demand and consumption can be expected. The reduction of the energy demand ranges, with respect to the baseline model, from 31.0% currently to 39.1% in 2080, while energy consumption changes from 40.2% to 62.0% in 2080.

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1. Introduction

Currently, there is a global need to reduce greenhouse gas emissions, and consequently, global energy consumption. According to the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), 32% of global primary energy was spent by buildings, producing 19% of global emissions in 2010 [1]. Currently, these values keep rising, so the chances of meeting the targets agreed in the 2020 Climate and Energy Package [2], extended to 2030 [3], are fading away as the deadlines come ever closer.

Energy efficiency in buildings keeps improving because of policy action and technological advances. However, these policies have focused mainly on building envelopes, rather than on the HVAC systems, which have one of the highest consumptions in building facilities [4]. According to the International Energy Agency (IEA), space heating accounted for 51% of energy consumption, while space cooling accounted for 3%, because the majority of the countries involved had cold climates [5].

On the other hand, the current regulations about HVAC systems in Spain (RITE by its acronyms in Spanish) [6] have established setpoint temperatures that keep operative temperatures between restrictive limits (21–23 °C in winter, and 23–25 °C in summer), making sure that occupants achieve thermal comfort. However, the high consumption needed to keep temperatures within that narrow threshold is not considered in the current regulation.

Mixed mode buildings operate with natural ventilation and air conditioning. The priority is using natural ventilation when outdoor temperatures are acceptable, and air conditioning when they are not. In large buildings, only the externally facing areas might use natural ventilation, so this operation mode is mainly focused on mid and small/scale buildings. It is classified into three modes:

- Concurrent: when air conditioning and natural ventilation can work at the same time and within the same space.
- Change-over: when air conditioning and natural ventilation can work for the same space, but not at the same time.

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Nomenclature

Acronyms

HVAC	Heating, Ventilating and Air Conditioning
ACCIM	Adaptive-Comfort-Control-Implemented-Model
AR5	Fifth Assessment Report
IPCC	Intergovernmental Panel on Climate Change
IEA	International Energy Agency
RITE	Spanish HVAC Systems Regulation (In Spanish: Reglamento de Instalaciones Térmicas en Edificios)
INE	Spanish National Statistics Institution (In Spanish: Instituto Nacional de Estadística)
CTE	National Building Code (In Spanish: Código Técnico de la Edificación)
ASHRAE	American Society of Heating, Refrigerating and Air-conditioning Engineers
EER	Energy Efficiency Ratio
COP	Coefficient of Performance
AHU	Air Handling Unit
VRF	Variable Refrigerant Flow
GRC	Glass Reinforced Concrete
MBE	Mean Bias Error
CV(RMSE)	Coefficient of Variation of the Root Mean Square Error
SCATs	Smart Control and Thermal Comfort
EPW	Energy Plus Weather
HadCM3	Hadley Centre Coupled Model 3
ACH	Air Changes per Hour

Symbols

Θ_{imax}	upper comfort limit temperature (°C)
Θ_{imin}	lower comfort limit temperature (°C)
Θ_{rm}	running mean outdoor temperatures (°C)
Θ_{ed-1}	average outdoor temperature from the previous day (°C)
Θ_{ed-2}	average temperature of 2 days before (°C)
T_{out}	outdoor temperature (°C)
T_{op}	indoor operative temperature (°C)
S_{ac}	adaptive cooling setpoint temperature (°C)
S_{ah}	adaptive heating setpoint temperature (°C)

– Zoned: when air conditioning and natural ventilation work in different spaces.

The suitability of each operation mode depends mainly on the type of building, the climate and the expectations of the occupants. For example, in concurrent mode, the HVAC system might provide additional ventilation or cooling, while occupants can open windows to achieve thermal comfort. Change-over mode is commonly used in individual offices with operable windows and personal air conditioning units that switch off when a sensor perceives that a window has been opened. Zoned mode might be suitable for buildings where occupants in different rooms have different preferences regarding conditioning strategies to achieve thermal comfort.

Mixed mode buildings have already been widely studied in terms of energy savings [7–9]. However, in terms of thermal comfort, there is still no consensus regarding how mixed mode buildings should be assessed considering natural ventilation and air conditioning separately. There is a similar lack of consensus about whether the adaptive comfort approach is suitable for both modes of operation. Several field studies in mixed mode buildings have been made, although there has been disagreement when some found a unique model for both modes of operation [10,11] and others did not [12]. Other authors considered that mixed mode buildings should be studied separately for both modes of operation, so developed comfort models for air conditioning and natural ventilation [13–15]. The results were consistent with this, with occupants' actual thermal sensation and acceptance varying when operation modes changed from air conditioning to natural ventilation, or vice versa. But, in general, the adaptive model was more suitable for mixed mode buildings [16]. Furthermore, it is necessary to consider that people might be used to using natural ventilation or air conditioning. In this way, people who tried to adapt their thermal sensation using adaptive comfort strategies more than others were found to switch on the air conditioning less frequently [17]. Since adaptive models might be more suitable for mixed mode buildings, there must be adaptive opportunities. Otherwise, perceptions of overheating could be intensified [18].

The adaptive approach is commonly applicable in naturally ventilated buildings, establishing a close relationship between indoor and outdoor environmental conditions. Hence, occupants are used to feeling a wider range of temperatures than occupants in fully air-conditioned buildings. As a result, their comfort threshold is wider and is dynamic depending on the outdoor temperature [19,20].

According to data from the Spanish national statistics institution (INE by its acronym in Spanish), 30% of the buildings were constructed after RITE and 55% after the current national building code [21] (CTE by its acronym in Spanish) came into force. Thus, a great number of buildings do not need energy retrofitting and have relatively recent facilities, so one of the most feasible solutions is varying the setpoint temperatures of existing facilities.

The potential energy saving from varying setpoint temperatures has been quantified in several studies: a reduction of 45% in energy consumption was achieved by adjusting heating and cooling setpoint temperatures to 20 °C and 26 °C, respectively [22] and depending on the analysed zone, between 32% and 73% was reduced by adjusting heating and cooling setpoint temperatures to 18.3 °C and 27.8 °C [23]. However, these setpoint temperatures were fixed, unlike the ones when the adaptive comfort approach is applied. This has also been carried out in other studies, where the lower adaptive comfort limit of the model developed for the Netherlands [24], established in the ISSO 74 standard [25], was used as the heating setpoint temperature. This study resulted in a 74% reduction in energy consumption [26]. This concept of energy demand, which considers the application of adaptive comfort standards, might lead to a new definition of fuel poverty [27], which is analysed in future scenarios [28]. There is a lack of research in this field in Spain, as the only study where energy demand was quantified, estimated a reduction of between 20% and 80% in heating and cooling, respectively [29]. However, in this study, the simplified method of the ASHRAE 55–2017 standard [30] was applied. This method allows calculating the prevailing mean outdoor temperature based on the daily mean. As such, the setpoint temperatures varied each day. The most similar study to the one presented in this research was also made in Seville. This study, once a thermal comfort model for mixed mode buildings was developed using field studies based on Griffith's comfort equation [10], saw the neutral temperatures obtained set as setpoint temperatures for heating or cooling depending on the season [31]. After this, energy consumption using actual setpoint temperatures was compared with energy consumption when using adaptive-model-based setpoint temperatures, obtaining energy savings of 27.5% in cooling and 11.4% in heating. The average cooling and heating actual setpoint temperatures were 22.3 °C and 23.5 °C, while the adaptive-model-based ones were 24 °C and 21.5 °C, respectively. Another research project previously studied the use of adaptive-model-based setpoint temperatures, with the difference that the buildings studied were fully air-conditioned [32]. In this case, setpoint temperatures were based on a new adaptive model they developed,

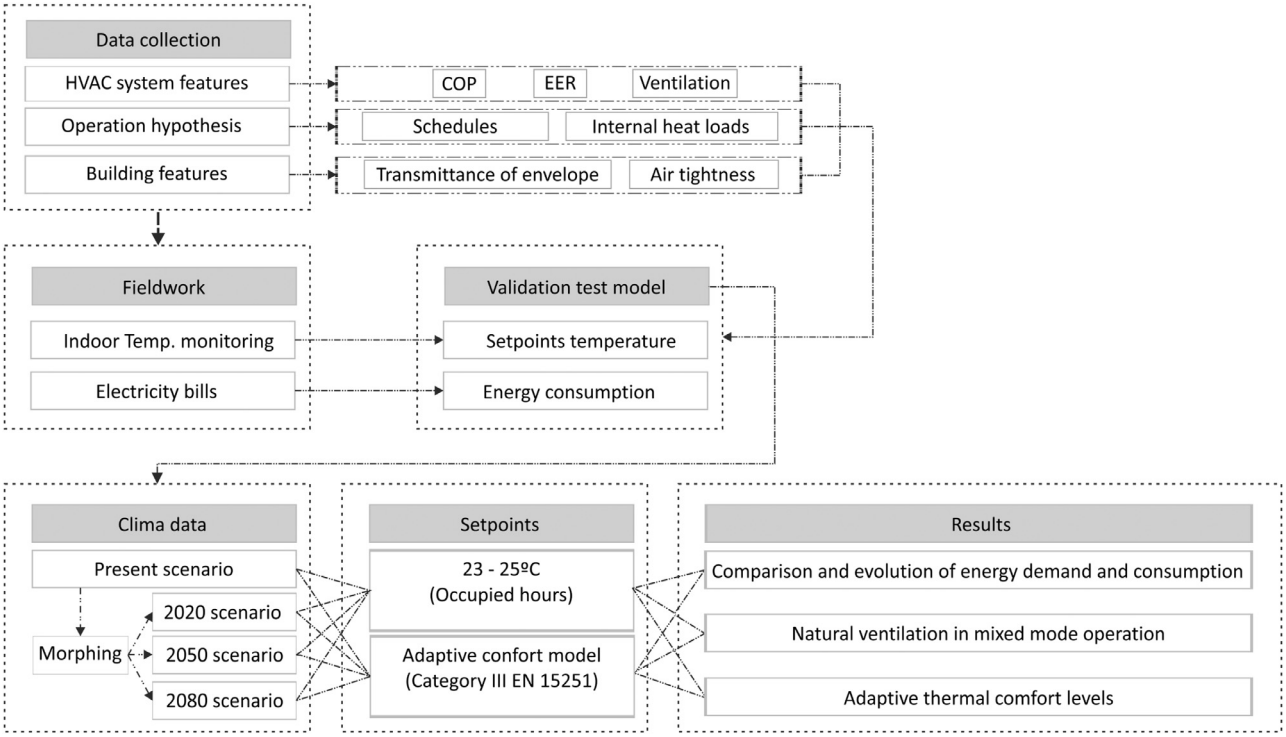


Fig. 1. Methodology flow chart.

but the cooling setpoints were higher, reaching 2 °C to 5 °C over the existing baseline setpoint temperature of 23 °C. However, this study does not consider the application of setpoint temperatures based on neutral temperatures, but rather comfort limits as per EN15251:2007 [33]. Thus, it applies less conservative setpoint temperatures while still prioritizing thermal comfort, but where temperature gaps between outdoors and indoors are smaller.

The objective of this study is to quantify energy savings and adaptive comfort levels by applying an adaptive comfort control, based on daily setpoint temperatures. This opens up to the concept of adaptive energy consumption [34], considering the mixed mode in buildings, while identifying its potential in the scenarios of 2020, 2050 and 2080.

2. Methodology

A methodology based on data collection, fieldwork, calibration, validation and simulation stages of the model in present and future scenarios has been made to meet the objectives of this study (Fig. 1).

In the first stage (data collection and fieldwork), data regarding HVAC system features, operation hypothesis and building features were collected. HVAC equipment was identified by visiting the building, allowing the determination of Energy Efficiency Ratio (EER) and Coefficient of Performance (COP) values by means of manufacturer's data sheets; the ventilation meanwhile, is made by using an Air Handling Unit (AHU). The internal loads of lighting, equipment and occupation were quantified; and the schedules and setpoint temperatures used were observed. The constructive characteristics of the envelope meanwhile, were determined based on the Design Project. In order to validate the model in the next stage, the indoor temperatures in conditioned and not-conditioned rooms along with the outdoor temperatures were monitored and electricity bills were obtained for have the real monthly consumption.

In the second stage (calibration and validation of the simulation model), the data measured and simulated regarding indoor temperature and energy consumption were compared to confirm that the model provides reliable results. The ASHRAE Guideline 14–2014 was used for this purpose [35].

In the third stage (simulation in present and future scenarios in mixed mode), the building has been simulated under current operation and the adaptive control in mixed mode. The heating and cooling setpoint temperatures for the current operation were 23 and 25 °C respectively while for the mixed mode, these were based on the upper and lower limits of the EN15251:2017 adaptive model for category III [33]. The mixed mode models were run in the present scenario and for future scenarios of 2020, 2050 and 2080 [36].

In the fourth and final stage (results), energy demand and consumption were analysed and compared under current operation and mixed mode with adaptive setpoint temperatures in the present and the future scenarios. Alongside this, the potential and the hours of use of natural ventilation were studied during the whole year considering climate change. At the end of this step, the adaptive comfort levels were connected with the energy consumption needed to maintain the room within the comfort zone.

2.1. Data collection and field work

The case study building is located in Seville, in the south-west of Spain, with mild, humid winters and dry, very hot summers (Köppen-Geiger classification: Csa). Global warming is especially important in this area [37]. The whole study took place on the 4th and 14th floors of the building, each with an area of 309 m^2. The building has 4 exposed façades, although half of the one that faces north-east contains the building's core and communal corridors, which are non-conditioned zones. The building currently does not work in mixed mode, so there is no window opening.

Data was collected from the building's architectural project, interviews with the occupants and monitoring of the variables. The building features' data was obtained from the architectural project (Table 1). HVAC systems data was also taken from the architectural

Table 1
Envelope characteristics, HVAC systems and loads.

Envelope characteristics	Layers	Thickness (mm)	U-value (W/m^{2}K)
Façade	GRC Stud frame panels	100	0.76
	Air chamber	70	
	Mineral wool insulation	40	
	Plasterboard	13	
Openings	Glazing: 6 + 12+6 mm[1]	–	2.82
	Aluminum frame[2]	–	4.72
Ceiling/floor	Plasterboard suspended ceiling	15	1.38
	Enclosed air chamber	450	
	Concrete slab	300	
	Enclosed air chamber	150	
	Steel-clad particleboard raised floor	30	
HVAC systems		Schedules	Setpoint
	Heating	9 am to 7 pm	23 °C
	Cooling		25 °C
	Ventilation		0.386 m3/s
Loads		Schedules	(W/m^2)
Occupancy	Offices	9 am to 2 pm and 4 pm to 7 pm	6.2
	Open workspaces		5.6
Lighting	Offices	9 am to 2 pm and 4 pm to 7 pm	12.1
	Open workspaces		10.9
Equipment	Offices	9 am to 2 pm and 4 pm to 7 pm	4.6
	Open workspaces		4.2

project, and the matching between the actual and projected HVAC system was verified through fieldwork. The heating and cooling are provided by a Variable Refrigerant Flow (VRF) system, with EER and COP values of 4.42 and 4.95, respectively. The mechanical ventilation system is built with a constant air flow rate of 0.386 m^3/s. The working periods and setpoint temperatures were determined through an interview with the building manager, who indicated that systems are kept working continuously from 9am to 7pm on weekdays and are shut down on weekends, while the heating and cooling setpoint temperature were respectively 23 °C and 25 °C and were used without any distinction for open or closed offices (Table 1). The manager also mentioned that the windows were always kept closed and the shutters always kept open. So currently, the building never works in mixed mode. The window-to-wall ratio was 0.28, and the glazed area that opened was 37 m^2, which represented 60% of the total glazed area.

The occupancy was obtained by counting the office workers in each room, considering the single closed offices and the open offices separately. Thermal loads for each space were determined by averaging similar spaces (Table 1). Occupancy schedules were obtained through interviews, where the occupants stated that the working day started at 9am and ended at 7pm, with a break for lunch between 2pm and 4pm. Lighting and general equipment were only switched on during occupied periods. As weekends were not working days, there was no occupancy and so, no use of lighting and equipment (Table 1).

In this process, the temperatures were monitored and electricity bills collected. The monitoring consisted in measuring the outdoor dry bulb temperature and indoor air temperature in an occupied room with air-conditioning and a non-occupied room without HVAC systems (Fig. 2). The air-conditioned space was on the 4th floor, the non-air-conditioned area was on the 14th floor and the roof (where outdoor temperature was measured) was on the 2nd floor. The monitoring process began on 29/11/2016 and lasted until 20/06/2017, recording the indoor and outdoor air temperatures every day in 1 h intervals with a total of 14,616 data sets. The indoor temperature was measured using HOBO U12-012 sensors, and the outdoor temperature with a HOBO Pendant data logger 8K-UA-002-08 sensor, both with a ± 0.7 °C accuracy. The sensors were previously calibrated to reduce errors in the measurement process. Sensors were deployed as per the indications of the ASHRAE 55–2017 Standard, Section 7.3.2, Physical measurement positions within the building [30]. In all cases, sensors were

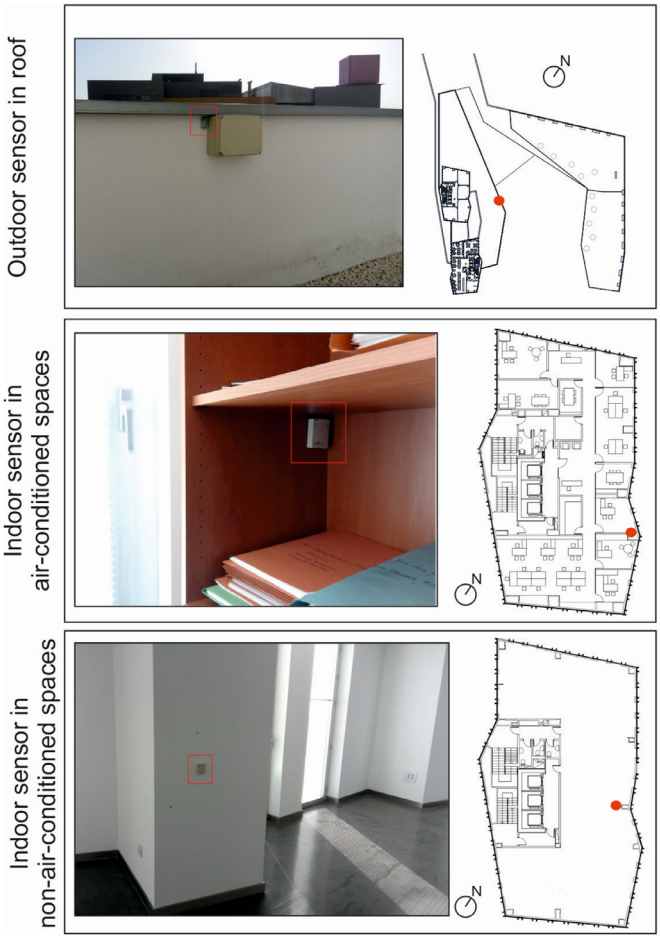
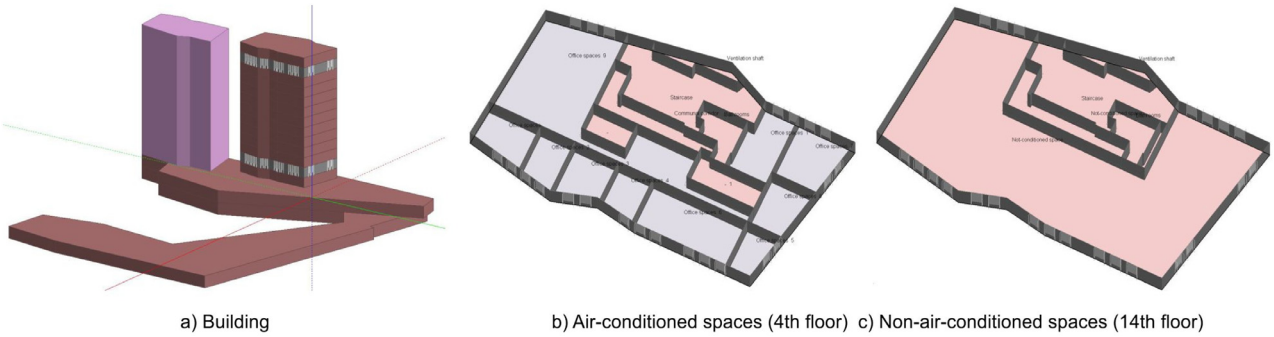


Fig. 2. Situation of the measurement cells within the building.

Table 2
Validation of the simulation model.

Temperature	Temperature	MBE	CV(RMSE)
	Outdoor	7.4%	21.9%
	Conditioned indoor	−3.2%	8.7%
	Not-conditioned indoor	1.4%	9.0%
Energy consumption	Energy consumption	Measured (kWh/year)	Simulated (kWh/year)
	Year 2015	365,683	334,408
	Year 2016	356,086	



a) Building b) Air-conditioned spaces (4th floor) c) Non-air-conditioned spaces (14th floor)

Fig. 3. Simulation model in Designbuilder software.

positioned strategically to not to receive external heat sources, and at a height of 1.1 metres from the floor.

Further information on the actual energy consumption data was collected using electricity bills provided by the occupants. This data was collected to validate the simulation model in the following stage, comparing the measured data and the simulation results.

2.2. Validation of the simulation model

The building performance simulation model was validated using the indoor and outdoor temperatures and energy consumption (Table 2). Regarding temperature, recommendations from ASHRAE Guideline 14–2014 [35] were followed. Some variance can be seen mainly in the indoor conditioned and outdoor temperatures, as the temperature measured is lower and higher than simulated in winter and summer respectively in case of indoor conditioned temperature, and only higher than simulated in summer in the case of outdoor temperature.

However, this variance is not significant, as the Mean Bias Error (MBE) and the Coefficient of Variation of the Root Mean Square Error (CV(RMSE)) satisfied the respective 10% and 30% limits [35]. Thus, the simulated data was reliable and there was no need to make further adjustments to calibrate the simulation model.

2.3. Simulation process

Simulations in present and future scenarios were run, considering the validation of the simulation model (Fig. 3) in the current state. The software used was DesignBuilder, which runs the Energy Plus calculation engine. The results were obtained on an hourly basis, and to make sure that the results were sufficiently accurate, simulation steps were set to 6 min intervals. In order to compare the fixed setpoint (23–25 °C) with the adaptive comfort algorithms, daily running mean temperatures were made for the present and future scenarios, as described in the following sections.

2.3.1. Calculation of adaptive setpoint temperatures

Adaptive comfort models work properly in naturally ventilated buildings, considering adaptive opportunities regarding behaviour and expectations. The main adaptive comfort standards are the ASHRAE 55–2017 and EN15251:2007 standards; however, the applicability of using these standards in mixed mode buildings is still to be resolved [38]. In this case, the EN15251 adaptive model has been applied. This model was developed from the European Smart Control and Thermal Comfort (SCATs) project. The selection of this model is based on its similarity with the case study (the SCATs project was focused on 26 European offices), as during this project an adaptive comfort algorithm (ACA) was developed for mixed mode buildings following recent research, using EN15251 in the same climate in Spain for mixed mode building automation systems [39].

The EN15251ś adaptive model is applicable in spaces where occupants have metabolic rates ranging from 1.0 to 1.3 met. Occupants are free to adapt their clothing to the indoor and/or outdoor thermal conditions. Natural ventilation can be controlled by occupants. While there is no mechanical cooling or heating system in operation. Thus, in this study, EN15251 has not been strictly applied, as mixed mode considers both air conditioning (by using adaptive setpoint temperatures) and natural ventilation modes. The adaptive setpoint temperatures can be defined as setpoint temperatures to keep indoor operative temperature within the adaptive thermal comfort zone, and thus, achieve adaptive thermal comfort.

The calculation of the adaptive setpoint temperatures has been made following the calculation procedure of the adaptive comfort limits for Category III, used for existing buildings. See the following Eqs. (1) and (2):

$$\text{Upper comfort limit} : \theta_{\text{i}}\,\text{max} = 0.33 * \theta_{rm} + 18.8 + 4 \quad (1)$$

$$\text{Lower comfort limit} : \theta_{\text{i}}\,\text{min} = 0.33 * \theta_{rm} + 18.8 - 4 \quad (2)$$

Where θ_{i} max is the upper comfort limit temperature and θ_{i} min is the lower comfort limit. Both are measured in °C. θ_{rm} is the running mean outdoor temperature of the day in question. It is also in °C and can be calculated using the following Eq. (3):

$$\theta_{rm} = (\theta_{ed-1} + 0.8 * \theta_{ed-2} + 0.6 * \theta_{ed-3} + 0.5 * \theta_{ed-4} + 0.4 * \theta_{ed-5} + 0.3 * \theta_{ed-6} + 0.2 * \theta_{ed-7})/3.8) \quad (3)$$

Where $\theta_{\text{ed-1}}$ is the average outdoor temperature from the previous day, $\theta_{\text{ed-2}}$ the average temperature of 2 days before and so on. The applicability of the model is also limited regarding the running mean outdoor temperature. In case of the upper comfort

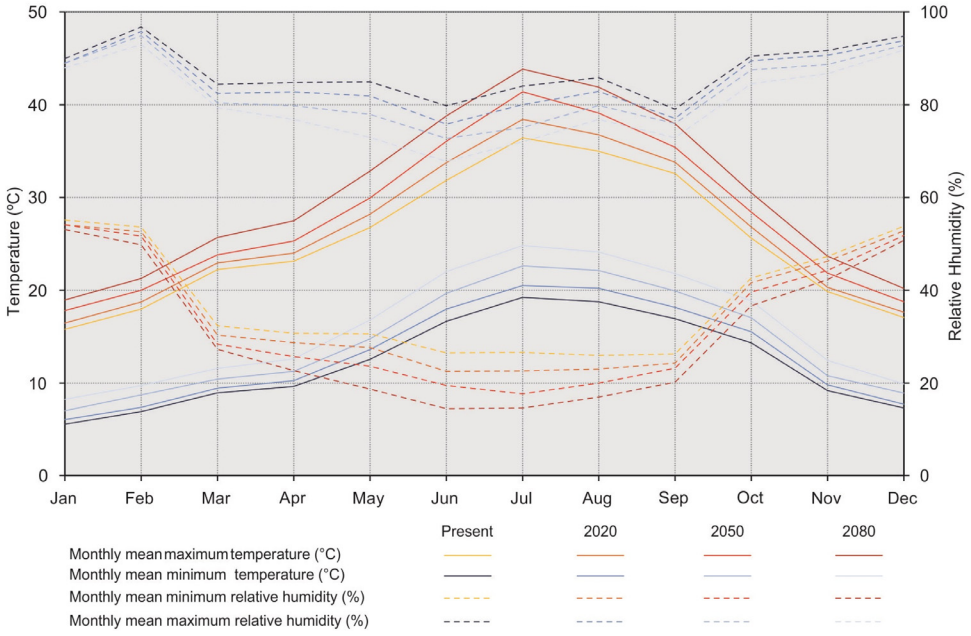


Fig. 4. Current, 2020, 2050 and 2080 temperatures and relative humidity.

limit, the running mean outdoor temperature range must be from 10 °C to 30 °C, and with the lower limit, it must be from 15 °C to 30 °C; otherwise, the model is not applicable when these temperatures are exceeded. When the running mean outdoor temperature falls outside these ranges, the comfort temperatures obtained from the adaptive comfort model are used in these limits. When the mean outdoor temperature for the lower limit is under 15 °C and for the upper limit is below 10 °C, the setpoint temperatures have been set at 19.75 °C and 26.10 °C. When over 30 °C, the setpoints of the running mean outdoor temperatures have been set at 24.7 °C and 32.7 °C. As running mean outdoor temperature varies on a daily basis, there is a daily heating and cooling adaptive setpoint temperature. Thus, 365 heating and cooling adaptive setpoint temperatures have been applied in the simulation model by using an EnergyPlus text-based Compact Schedule.

2.3.2. Present and future scenarios

In order to simulate the building in future scenarios for 2020, 2050 and 2080, a morphing process [40] by means of the software CCWorldWeatherGen [36] was run. By using this software, present EnergyPlus Weather (EPW) data can be turned into future projections of the greenhouse gas emissions group A2, which are considered by the Intergovernmental Panel on Climate Change (IPCC) as medium-high. This software considers the combination of the A2a, A2b, and A2c guidelines of the UK Met Office's Hadley Centre Coupled Model 3 (HadCM3) model. Output data provides three EPW files, with weather data from the present day converted into data for 2020, 2050 and 2080.

The HadCM3 is probably the most commonly used model to simulate future scenarios. However, it is necessary to be aware that the resolution of the HadCM3 model is mainly used on a global scale (HadCM3 model covers a finite grid point model covering an area of 2.5° latitude by 3.75° longitude, with a resolution of around 300×300 km^2 in the whole world); EPW files, which are used in the morphing process, are generated from data measured at weather stations which are generally on the periphery of the cities, so urban heat islands, among other microclimate effects, are not taken into account. Also, the HadCM3 model cannot consider extraordinary natural phenomena, as it only predicts future trends from average values.

The Climate in the present scenario is mild in winter, with a lowest monthly mean minimum temperature of 5.57 °C in January, and severe in summer, with a highest monthly mean maximum temperature of 36.43 °C in July (Fig. 4). As expected, the situation grows in severity with the impact of global warming, considering that the previously mentioned temperatures rise to 6.07 °C, 7.02 °C and 8.25 °C in the case of monthly mean minimum temperature, and to 38.42 °C, 41.39 °C and 43.84 °C, by 2020, 2050 and 2080, respectively. This severity does not grow equally for winter and summer, as the temperature increase from the present day to 2080 rises by 2.68 °C in the case of January and by 7.40 °C in the case of July. In terms of annual mean temperature, it rises from the current 18.36 °C to 19.36 °C, 20.89 °C and 22.74 °C in 2020, 2050 and 2080. Relative humidity shows a more irregular trend with some ups and downs throughout the year, with maximum and minimum monthly mean values from 88% to 90% and from 53% to 55%, respectively, for all scenarios in January. In July, the relative humidity range stretches, covering maximum and minimum monthly mean values from 67% to 80% and from 14% to 26%.

The current adaptive comfort model can assess adaptive thermal comfort levels in present scenario. However, the thermal acceptability and comfort thresholds of human beings might change as they adapt to increasing temperatures caused by climate change. Therefore, the calculation of adaptive thermal comfort levels in future scenarios is limited as the adaptation to the increasing temperatures has not been considered. This might lead one to expect that, in case that thermal adaptation was considered, energy saving potential might grow, as human beings would consider higher temperatures acceptable and so cooling adaptive setpoint temperatures could be higher than actually calculated.

2.3.3. Mixed mode with adaptive comfort control

The energy saving potential has been quantified by comparing the baseline model (which is the model based on actual building features and operation hypotheses, as defined in Section 2.1 and Table 1) with the adaptive comfort control implemented model (ACCIM), which has been set over the baseline model, with the specific parameters (Table 3):

- Setpoint temperatures: adaptive setpoint temperatures have been applied, instead of considering 23 °C and 25 °C as

Table 3
Mixed mode and air conditioning operation hypothesis.

Natural ventilation mode (only airflow through windows)	Ventilates if	S_{ah}-1 °C < T_{out} ≤ S_{ac}
Air-conditioning mode	Cooling on if	T_{op} > S_{ac}
	Heating off if	T_{op} < S_{ah}

heating and cooling setpoint temperatures respectively. These adaptive setpoint temperatures have been calculated by means of the upper and lower comfort limits calculation procedure set out in EN15251. In order to keep all the hours within the comfort zone, heating and cooling were allowed throughout the entire year. The reason of this lies in the narrow setpoint threshold (23–25 °C) established in the current national HVAC systems regulation, that might lead to even using heating in summer and cooling in winter.

- Mixed mode: when outdoor temperatures were acceptable (i.e. outdoor temperature (T_{out}) was lower than operative temperature (T_{op})), all windows could to be opened, with the following exceptions: firstly, when outdoor temperatures were 1 °C less than adaptive heating setpoint temperature, windows were closed to prevent excessive cold; and secondly, when wind speed exceeded 1.5 m/s, windows started to close gradually until 6 m/s, where they were closed completely. As windows were hinged on the bottom for security reasons, they did not open completely and so, natural ventilation was limited. To consider this potential fact for mixed mode purposes, the window opening percentage was set as up to 25%. This operation was used no matter what time it was, on weekdays from May to September. When outdoor temperatures were not acceptable (i.e. when the outdoor temperature was higher than operative temperature), windows were closed to prevent warm air from entering. If the outdoor temperature was higher than the operative temperature, but the operative temperature was still below cooling setpoint temperature levels, air conditioning did not switch on and windows were kept closed. Thus, air conditioning only switched on (i.e. change-over mode was applied) during the occupied periods, if operative temperatures were higher than the adaptive cooling setpoint temperature (S_{ac}), or lower than the adaptive heating setpoint temperature (S_{ah}). This has been applied in addition to mechanical ventilation and infiltrations, so even when the windows were closed, there was still a minimum supply air rate. The ventilation rates are calculated using wind and buoyancy-driven pressure, opening sizes and operation and crack sizes using the EnergyPlus Airflow Network.

3. Results and discussion

3.1. Comparison and evolution of energy demand and consumption

Energy demand (latent+sensible) and consumption are compared considering the baseline model (conventional energy demand and consumption) and ACCIM (adaptive energy demand and consumption). Table 4 shows the results of the simulations taking the baseline model in each climate scenario as the reference value in the calculation of the percentages. The reduction of energy demand varies between 74.6% and 62.5% under cooling mode, between 57.9% and 43.1% in heating mode, and between 70.5% and 60.9% for both modes together (total column), depending on the climate scenario.

In the case of energy consumption, there is a similar trend, as energy savings account for 59.5% to 36.7% in cooling, 73.1% to 62.3% for heating and 59.8% to 38.0% for both modes together. As requiring occupants to act in an ideal way is extremely difficult, the most feasible option might be to control the indoor operative temperature to be within adaptive thermal comfort zone and to switch the conditioning strategy to ventilation when possible. This important energy saving might be achieved with no investments in new HVAC equipment or retrofitting measures other than a person in charge of adjusting the setpoint temperatures and window opening, or even an automated system which could be manually controlled as well.

The relation between the hourly values of energy demand from the baseline model and ACCIM is shown in Fig. 5. The use of the ACCIM means that both the heating and cooling demands are reduced versus the baseline model. The use of cooling in reduced from 623 h for the current scenario to 431 for 2080. With regard to

Table 4
Comparison of energy demand and consumption.

Energy demand (kWh/m²·year)	Scenario	Model	Cooling		Heating		Total	
			kWh/m²·year	Reduction (%)	kWh/m²·year	Reduction (%)	kWh/m²·year	Reduction (%)
	Present	Baseline	61.46		23.24		84.70	
		ACCIM	15.59	74.6	10.67	54.1	26.26	69.0
	2020	Baseline	70.42		19.42		89.84	
		ACCIM	18.08	74.3	8.46	56.4	26.54	70.5
	2050	Baseline	79.37		14.57		93.94	
		ACCIM	27.09	65.9	6.13	57.9	33.22	64.6
	2080	Baseline	96.77		8.78		105.56	
		ACCIM	36.27	62.5	5.00	43.1	41.27	60.9
Energy consumption (kWh/m2·year)	Scenario	Model	Cooling		Heating		Total	
			kWh/m²·year	Reduction (%)	kWh/m²·year	Reduction (%)	kWh/m²·year	Reduction (%)
	Present	Baseline	16.36		2.68		19.04	
		ACCIM	6.63	59.5	1.01	62.3	7.65	59.8
	2020	Baseline	18.19		2.28		20.47	
		ACCIM	7.74	57.5	0.76	66.7	8.50	58.5
	2050	Baseline	20.26		1.71		21.97	
		ACCIM	11.48	43.3	0.46	73.1	11.94	45.7
	2080	Baseline	24.42		1.06		25.48	
		ACCIM	15.47	36.7	0.31	70.8	15.79	38.0

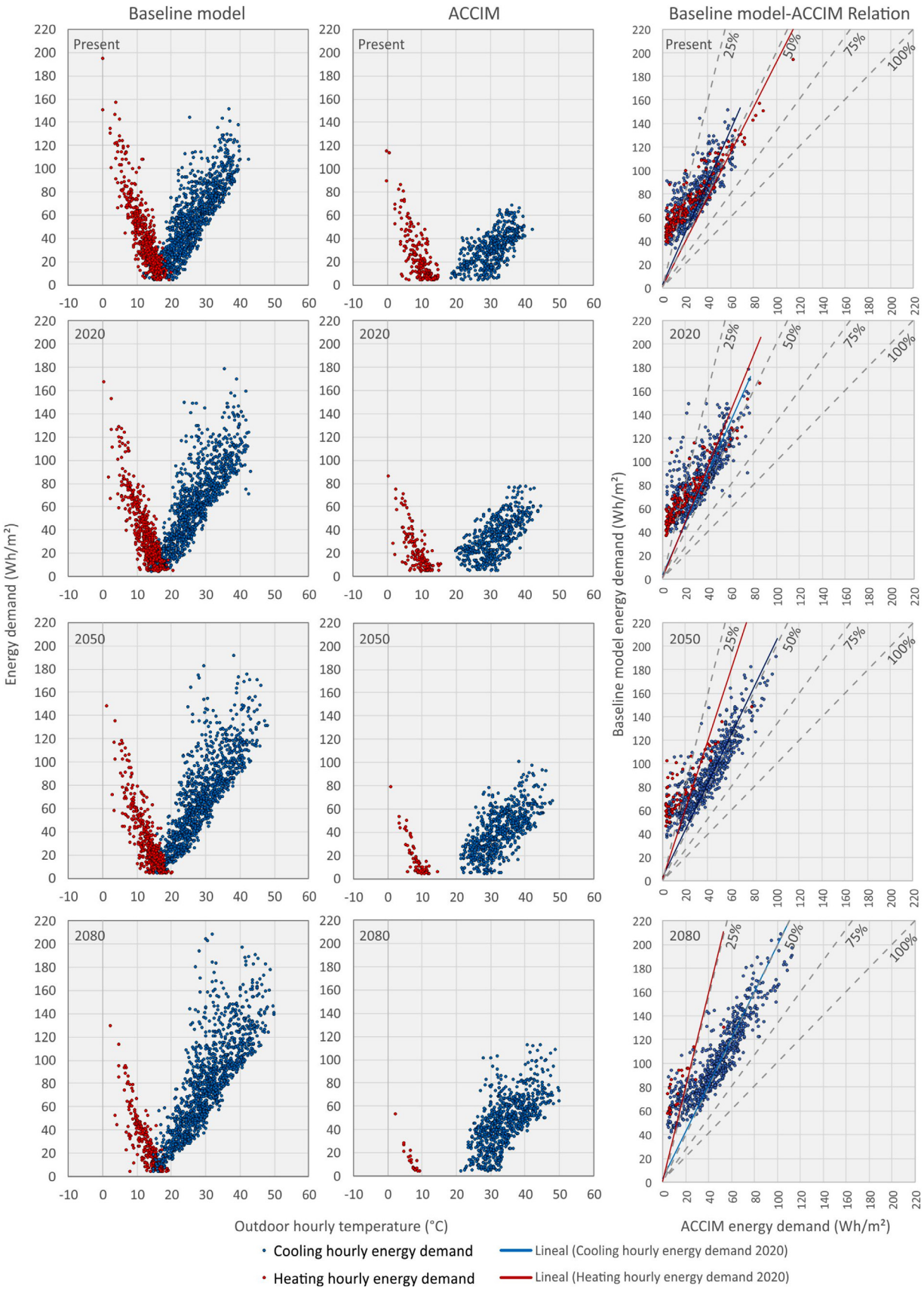


Fig. 5. 1st and 2nd columns from left to right: Relation between hourly energy demand and outdoor hourly temperature of baseline model and ACCIM in present and future scenarios. 3rd column from left to right: Relation between hourly energy demand from baseline model and ACCIM in present and future scenarios.

Table 5
Evolution of energy demand and consumption.

Model			Scenario						
			Present	2020		2050		2080	
			kWh/m^2·year	kWh/m^2·year	%	kWh/m^2·year	%	kWh/m^2·year	%
Energy demand (Wh/m^2·year)	Baseline	Cooling	61.46	70.42	14.6	79.37	29.1	96.77	57.5
		Heating	23.24	19.42	−16.4	14.57	−37.3	8.78	−62.2
		Total	84.70	89.84	6.1	93.94	10.9	105.56	24.6
	ACCIM	Cooling	15.59	18.08	16.0	27.09	73.8	36.27	132.7
		Heating	10.67	8.46	−20.7	6.13	−42.6	5.00	−53.1
		Total	26.26	26.54	1.1	33.22	26.5	41.27	57.2
Energy consumption (Wh/m^2·year)	Baseline	Cooling	16.36	18.19	11.2	20.26	23.8	24.42	49.3
		Heating	2.68	2.28	−14.9	1.71	−36.2	1.06	−60.5
		Total	19.04	20.47	7.5	21.97	15.4	25.48	33.8
	ACCIM	Cooling	6.63	7.74	16.7	11.48	73.2	15.47	133.3
		Heating	1.01	0.76	−24.8	0.46	−54.5	0.31	−69.3
		Total	7.65	8.50	11.1	11.94	56.1	15.79	106.4

heating, the hours are reduced from 328 h for the current scenario to 243 for 2080, thus indicating that both demands see important reductions when using ACCIM, as there is an hour percentage reduction of between 55.3% and 35.7% for cooling and 60.9% and 92.1% for heating. With regard to the demands, it is possible to see that the maximum hourly cooling demands fall from 55.0% and 45.8% between the current scenario and 2080, respectively, on using the ACCIM, passing from 151.41 Wh/m^2 to 68.09 Wh/m^2 and from 208.69 Wh/m^2 to 112.82 Wh/m^2. The minimum hourly demands fall by 12.0% in 2080 on using the ACCIM, but by using this in 2020 and 2050, the demands increase by 3.5% and 11.7%. The demand averages for the baseline model range between 54.52 Wh/m^2 and 80.10 Wh/m^2 for the present day and are offset, applying the mixed mode to between 44.4% for 2020 and 39.9% for 2050 (Fig. 5).

The heating demands also see substantial reductions on using the mixed mode and global warming, the maximum hourly demands are offset by between 80.72 Wh/m^2 for 2020 and 68.65 Wh/m^2 for 2050, representing between 58.9% and 40.8%, while the minimum demands had hardly any change, with the difference between −0.1% and 3.2%. However, the hourly demand average falls in a similar fashion to the cooling demand, with a percentage of between 40.9% (16.97 Wh/m^2 Present day) and 49.8% (14.13 Wh/m^2 2080), if the ACCIM is used (Fig. 5).

In Fig. 5, it can be seen that there is a future trend, in the baseline model, towards reducing the heating demand and increasing the cooling demand. The maximum hourly cooling demand passes from 151.41 Wh/m^2 under the current scenario to 208.69 Wh/m^2 for 2080, while the maximum heating from the baseline model is reduced from 194.41 Wh/m^2 to 129.72 Wh/m^2. The average hourly cooling meanwhile is increased by 25.58 Wh/m^2, while heating falls by 13.08 Wh/m^2. With the use of the mixed model and the adaptive setpoints, the increase of maximum hourly cooling demands is 12.54 Wh/m^2 less (68.09 Wh/m^2 currently, 112.82 Wh/m^2 2080). However, the reduction of the maximum hourly demands for heating is practically the same, as with the ACCIM, it passes from the current 115.10 Wh/m^2 to 53.26 Wh/m^2 in 2080. The average hourly demands for cooling under mixed mode increase by 15.71 Wh/m^2, while for heating they are reduced by 10.25 Wh/m^2 which implies that for cooling with the ACCIM, the increase of the current scenario to 2080 will be a lower average of 9.88 Wh/m^2, while the heating will be reduced by 2.84 Wh/m^2 less.

In the baseline model, cooling energy demand increases from 14.6% in the 2020 scenario to 57.5% in the 2080 scenario, while heating energy demand decreases from 16.4% to 62.2% (Table 4). Considering absolute values, the results depict that the increase in cooling energy demand and decrease in heating energy demand is not proportional, as the first one increases 35.3 kWh/m^2·a year, while the second one decreases about 14.5 kWh/m^2·a year. Thus, when considering both energy demands, the trend is rising, from 6.1% in the 2020 scenario to 24.6% in the 2080 scenario. With ACCIM, the cooling energy demand increases from 16.0% in the 2020 scenario to 132.7% in 2080, while the heating energy demand decreases from 20.7% in the 2020 scenario to 53.1% in the 2080 scenario.

The increase in the cooling demand in 2080 is less with ACCIM than in the baseline model, with a difference of 20.68 kWh/m^2·a year and 35.31 kWh/m^2·a year, respectively. On the other hand, the reduction in the heating energy demand trend is greater than the baseline with a reduction of 14.46 kWh/m^2·a year, while for the mixed mode it is 5.67 kWh/m^2·a year. Therefore, on considering both energy demands, the trend increases in both models, increasing by 20.86 kWh/m^2·a year for the baseline and 15.01 kWh/m^2·year for ACCIM in 2080 (Table 5).

In the case of energy consumption, the trend is similar to the energy demand. Considering the baseline model, cooling energy demand increases from 11.2% in the 2020 scenario to 49.3% in 2080; heating energy demand decreases from 14.9% in the 2020 scenario to 60.5% in 2080; and combining both different heating and cooling trends, the total energy demand increases from 7.5% in the 2020 scenario to 33.8% in 2080. Upon considering ACCIM, the cooling energy demand increases from 16.7% in the 2020 scenario to 133.3% in 2080; the heating energy demand decreases from 24.8% in the 2020 scenario to 69.3% in 2080; and combining both different heating and cooling trends, the total energy demand increases from 11.1% in the 2020 scenario to 106.4% in 2080.

The results also depict that the ACCIM is more resilient to climate change, despite the fact that an increase in energy demand and consumption can be expected. There is a reduction of the energy demand ranges, with regard to the baseline model, from 31.0% at present to 39.1% in 2080 and for energy consumption, from 40.2% to 62.0% in 2080.

3.2. Natural ventilation in mixed mode operation (ACCIM)

Natural ventilation in mixed mode is also affected by global warming (Fig. 6). As scenarios advance, cooling needs to start earlier and last longer (thus, the use of natural ventilation decreases), as well as reaching higher values. Under the present scenario, the daily use of natural ventilation switches to air conditioning mainly from July 20th to September 22th and reaches values of between 4.02 and 68.09, with an average of 30.88 Wh/m^2. In the 2020, 2050 and 2080 scenarios, this period starts earlier, around July 11th, June 14th and June 5th, and cooling energy demand reaches

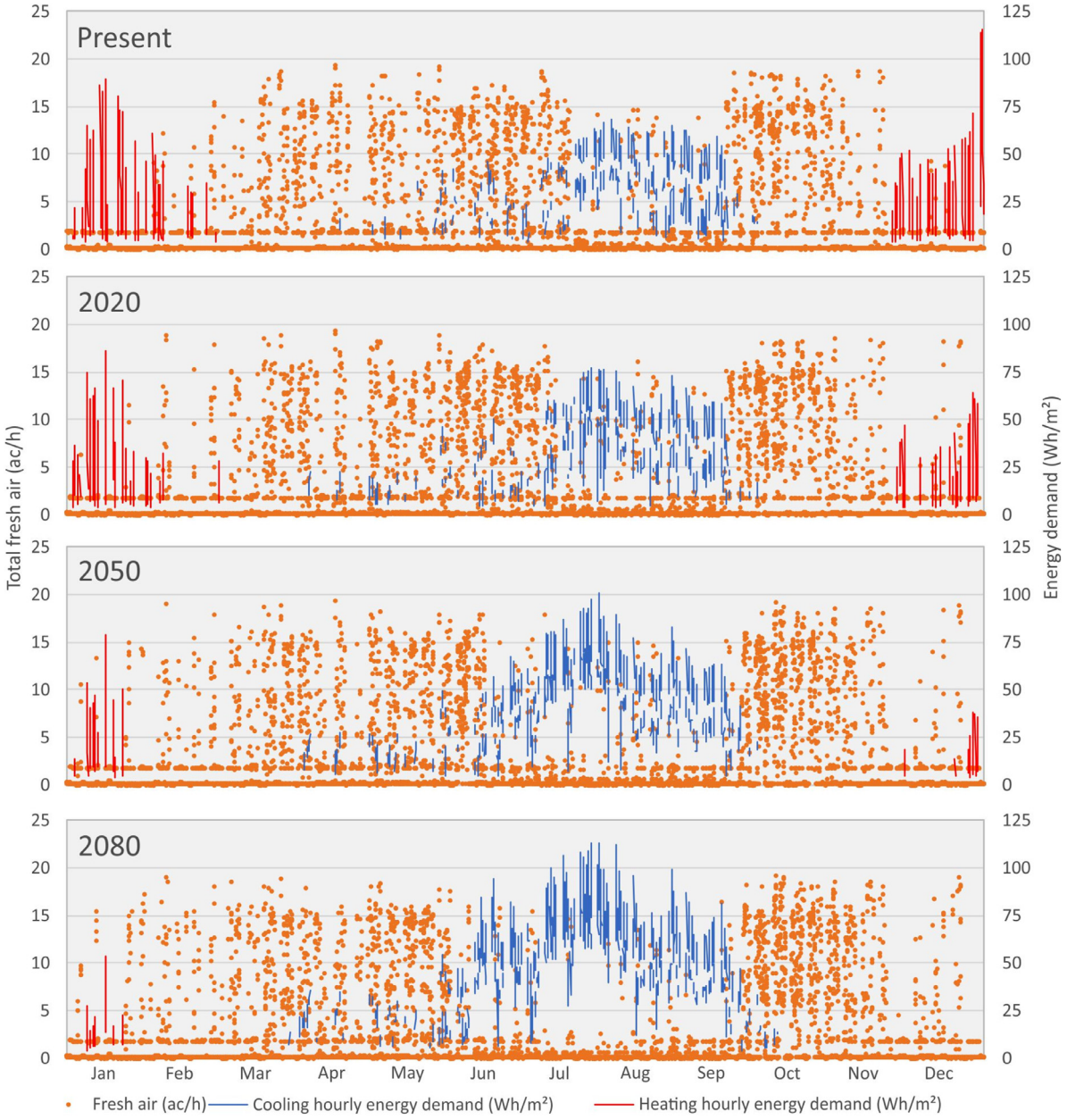


Fig. 6. ACCIM Mixed mode operation in present and future scenarios.

average values of 33.68 Wh/m^2, 40.07 Wh/m^2 and 46.59 Wh/m^2, with maximum values between 77.10 and 112.82 Wh/m^2. However, the end of this period varies slightly by about a week as the scenarios advanced, from September 13th to 20th. Climate change has an impact on the heating energy demand as well. As can be seen, frequently the maximum heating energy demand values decrease from 115.10 Wh/m^2 in the present scenario, to 85.79 Wh/m^2 in 2020, 79.06 Wh/m^2 in 2050 and 53.26 Wh/m^2 in 2080. Density of values further decreases, and the heating season narrows by around 3 weeks from the present to the 2020 scenario, and around 6 weeks from 2020 to 2050 and from 2050 to 2080. While at present, the heating season takes place from November 25th to February 15th, in the 2080 scenario it starts by January 10th and ends by January 28th.

The average air changes per hour (ACH) during occupation hours when the building activates the air-conditioning systems to reach the aforementioned demands, are around 1.70 and 2.07 ACH depending on the weather scenario. However, under free oscillation, the average air changes range between 5.64 and 5.96 with maximum values between 18.96 and 19.24 ACH, depending on the weather (Fig. 6).

The heating and cooling usage hours in the ACCIM are analysed for each month and each scenario separately (Table 6). As can be expected, climate change has an effect on the usage of heating and cooling by decreasing heating hours in cold months (from November to February) and by increasing cooling hours in hot months (from April to September). The change from the heating to cooling season can be found in March, with hours where heating is not necessary continues to grow more than the hours when cooling is required. This trend remains until 2050, when the number of hours with no need to use heating or cooling is 184. However, in 2080, the trend reverses when the aforementioned number of hours is 166 as the temperatures are too high, and summer starts earlier. On the other hand, the change from the cooling to heating

Table 6
Hours when heating or cooling is not necessary.

Month	Present	2020		2050		2080	
	Hours	Hours	$H_{present}$-H_{2020}	Hours	$H_{present}$-H_{2050}	Hours	$H_{present}$-H_{2080}
January	111	108	−3	137	26	158	47
February	121	139	18	156	35	160	39
March	163	180	17	184	21	166	3
April	173	148	−25	137	−36	125	−48
May	142	141	−1	133	−9	122	−20
June	106	108	2	55	−51	5	−101
July	59	40	−19	3	−56	1	−58
August	6	7	1	1	−5	2	−4
September	44	46	2	29	−15	24	−20
October	178	173	−5	172	−6	159	−19
November	153	164	11	172	19	176	23
December	97	118	21	147	50	165	68
Total	1353	1372	19	1326	−27	1263	−90

season can be found in October, where the balance of hours when cooling is necessary and heating is not, remains until 2080, when temperatures are too high again, and hours with no HVAC system usage decreases from 172 to 159.

The month when climate change has the severest impact varies depending on the scenario. Those months in the 2020, 2050 and 2080 scenarios are respectively April, July and June, with a reduction of 25, 56 and 101 h. On the other hand, December has the peak value in each scenario, with an increase of 21, 50 and 68 h respectively in the 2020, 2050 and 2080 scenarios.

Over the whole year, the 2020 scenario shows an overall increase of 19 h, but this trend reverses in the 2050 and 2080 scenarios, where the decrease is 27 and 90, using the present scenario as a reference point. Overall this denotes the resilience of this operation mode considering the abrupt increase in outdoor temperatures.

3.3. Adaptive thermal comfort levels

The main priority when setting adaptive setpoint temperatures was to keep hourly temperatures within adaptive comfort zones. Consequently, thermal comfort levels in the ACCIM are the highest in each scenario. Fig. 7 depicts the hourly indoor operative temperatures within the upper and lower adaptive comfort limits and the energy needed to keep the temperature within the comfort zone. Currently, 735 h of air-conditioning are needed to keep temperatures within the set thermal comfort ranges. 30.9% of the hours are for heating, with 69.1% for cooling. 72.0% of the hours use adaptive setpoints, 2.9% for heating with temperatures between 19.87 °C and 24.12 °C and the rest for cooling, with a temperature range between 27.43 °C and 32.69 °C. The remaining hours, where adaptive setpoints are not used, apply when the running mean outdoor temperatures are outside the application ranges of the adaptive comfort model in said limits. For cooling, no fixed setpoints appear, while for heating, they are used for 28.0% of the total air-conditioning hours (Fig. 7).

The air-conditioning hours fall by 19 h for 2020, when compared to the present day, using 64.8% of the adaptive setpoint hours. 2.9% are for heating, with values ranging between 20.54 °C and 24.51 °C and 61.9% of the time for cooling, with temperatures between 27.7% and 32.7%, while the static setpoints comprise 8.8% and 35.6% of the hours, respectively.

In 2050, the air-conditioning hours increase 27 h versus the current status, using 55.6% of the adaptive setpoint hours, 2.4% for heating with values between 20.79 °C and 24.70 °C and 53.3% of the time for cooling with temperatures over 28.03 °C. The fixed setpoints, meanwhile, comprise 8.8% and 35.6% of the hours, respectively.

In 2080, the total air-conditioning hours will increase by 90 h (825 h) versus the current status. It will only be possible to use the adaptive setpoints, for 34.3% of the hours, with 3.5% for heating adaptive setpoints with values between 20.52 °C and 24.70 °C and 30.8% for cooling with values between 28.57 °C and 32.56 °C.

It is possible to see in Fig. 7 that ACCIM currently makes it possible to use the adaptive setpoints well, mainly for cooling, representing 69.1% of the air-conditioning hours used. However, the increase in outdoor temperatures due to climate change, although it reduces the heating demands, increases the cooling demands. As a result, a substantial reduction in the hours the adaptive setpoints are used for cooling is produced, meaning in 2080, that air-conditioning equipment will only be used for 30.8% of all the hours.

4. Conclusions

This study sheds light on the quantification of energy demand and consumption through the use of an adaptive comfort control. The application of daily climate-based setpoints, permits better climate adaption than the use of fixed setpoints. This is reflected in the potential of ACCIM, as the reduction in the current demand (69.0%) and energy consumption (59.8%) are significant, on extending the comfort limits towards a better adaptation and interaction with the outdoors. It is such, that during a large part of the year, natural ventilation is capable of maintaining comfortable conditions inside, considerably reducing annual heating and cooling hours (735 h).

The results of this research, considering future climate change scenarios, are also enlightening with regard to the resilience and versatility of ACCIM. Despite the demand and energy consumption experiencing an increase due to global warming in the study's climate, the quantification model is more resilient than in the fixed setpoints, with the consumption levels much lower, with a maximum reduction of 62.0% in 2080. Although the outdoor climate gets hotter, the natural ventilation hours falls slightly (from 1353 currently to 1263 in 2080). This shows that the model is versatile to changing conditions, taking advantage of the natural ventilation regardless of the start of the winter or summer season and adapting the air-conditioning systems when the outdoor conditions are unfavorable. However, the adaptive models establish applicability ranges which have been seen to be left behind, especially in future scenarios. In this case, the running mean outdoor temperature is limited to 30 °C, which is why the model starts to work with fixed setpoint from this temperature upwards.

However, this research is just a starting point about the quantification of these adaptive setpoint based energy parameters. The building and the climate considered must be understood as testing

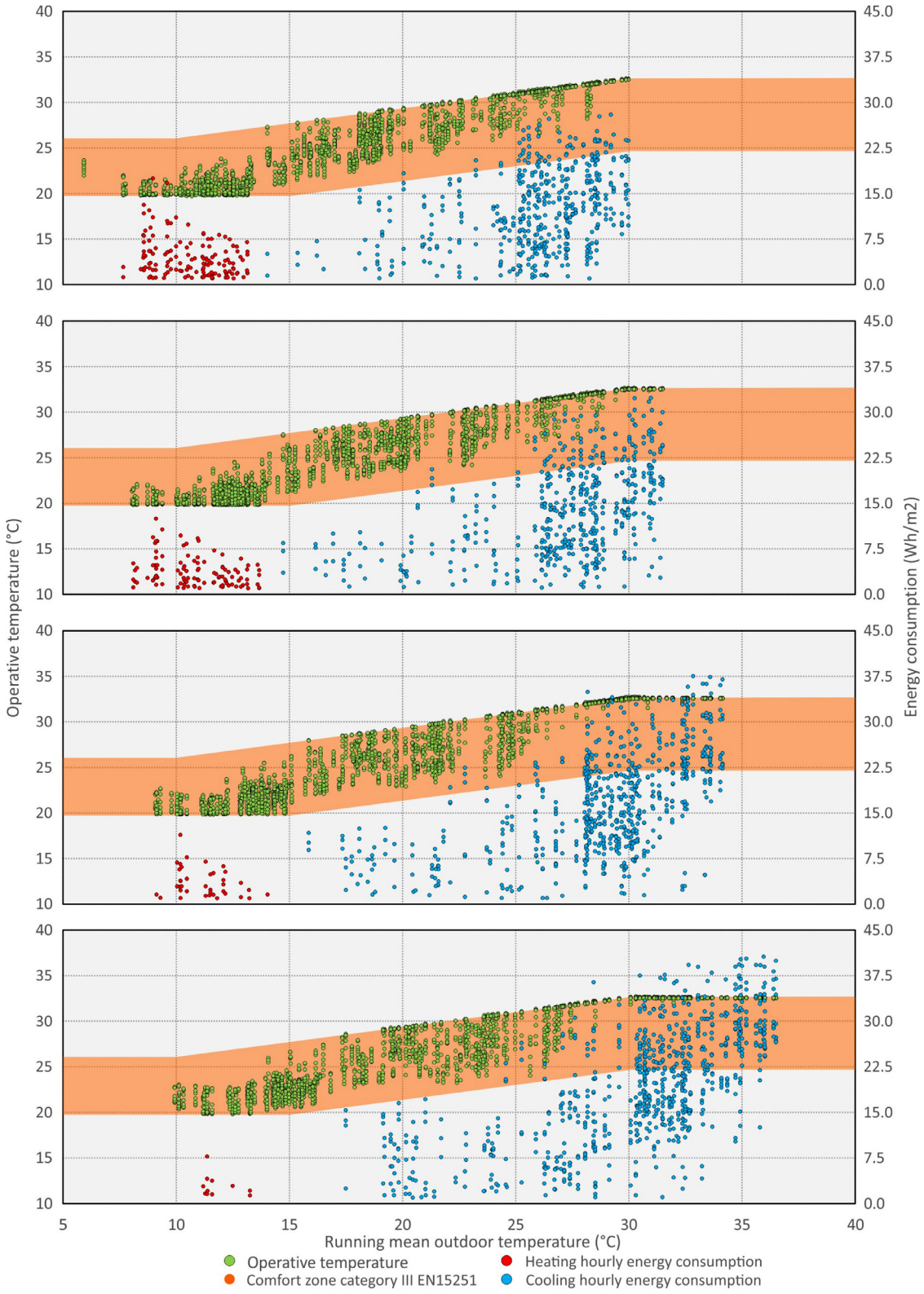


Fig. 7. Relation between hourly energy demand and outdoor hourly temperature of baseline model and ACCIM in present and future scenarios.

this concept. In this sense, a starting point for future investigation has been created. The extrapolation of the model to other climates or to another type of buildings will make out its potential in future studies. Detailed studies about applicability limits, thermal comfort surveys and the adaptation of users to future climates, are adaptable and would provide feedback to the quantification model which contributes to the adaptation and mitigation of climate change.

Conflicts of interest

The authors declare no conflict of interest.

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